Example 5e: Fiber-Matrix Debonding

This example problem involves the simulation of transverse fiber-matrix debonding in a SiC/Ti-21S composite. This type of failure has proven to be a major obstacle in the utilization of titanium matrix composites. MAC/GMC 4.0 incorporates two distinct fiber-matrix debonding models, each of which is based on the same overall concept of imposing a discontinuity or "jump" in displacement at a particular interface. This displacement jump is modeled as proportional to the stress at the interface and is not activated until the interfacial stress reaches a critical debond stress,

$$[u]^I = R\sigma\Big|^I \qquad\qquad \sigma\Big|^I \geq \sigma_{DB}\Big|^I$$

where $[u]$ is the resulting displacement component at interface I, σ is a particular stress component at interface I, σ_{DB} is the debond stress of interface I, and R is a debonding parameter for interface I. This interfacial representation has been employed by Jones and Whittier (1967), Aboudi (1987), Achenbach and Zhu (1989), and Wilt and Arnold (1996). In MAC/GMC 4.0, as was done by Bednarcyk and Arnold (2002), the debonding parameter R is permitted to evolve with time. The form of this time evolution distinguishes between the two debonding models within MAC/GMC 4.0.

First, the constant compliant interface (CCI) model employs,

$$\frac{\partial R(t)}{\partial t} = \Lambda \frac{\sigma(t)}{\mathrm{B}}$$

at a particular interface. The evolving compliant interface (ECI) model, on the other hand, employs,

$$\frac{\partial R(t)}{\partial t} = \Lambda \frac{\exp(t - t_{DB})}{\mathrm{B}} \qquad\qquad (t - t_{DB}) \geq 0$$

at a particular interface. Λ and B are additional parameters that characterize the behavior of a particular interface and t_{DB} is the time of debonding for the interface. Thus, the time dependence in the CCI model is implicitly based on the time dependence of the interfacial stress while the ECI model incorporates explicit time dependence in its evolution equation. The dependence of the CCI model on the interfacial stress causes this model to saturate to a steady state condition (when the parameters Λ and B are chosen properly). This characteristic is due to the fact that, as the parameter R rises with the rising interfacial stress, the interface becomes more and more compliant, causing the interfacial stress to level off. Once the interfacial stress stops increasing, the debonding parameter R can no longer increase, and a steady state condition is reached. Conversely, in the ECI model, with its explicit exponential time dependence, the debonding parameter R can continue to rise. As shown in this example problem, this ability allows the interfacial stress to unload in composite simulations involving the ECI model. For additional information on the CCI and ECI models, see the MAC/GMC 4.0 Theory Manual Section 5.4.

MAC/GMC Input File: `example_5e.mac`

```
MAC/GMC 4.0 Example 5e - Fiber-matrix transverse debonding
*CONSTITUENTS
  NMATS=2
```

```
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*RUC
  MOD=2 ARCHID=11 VF=0.35 R=0.9 F=1 M=2
*MECH
  LOP=3 REFTIME=64800.
  NPT=5 TI=0.,24000.,57600.,64800.,64908. MAG=0.,0.,0.,0.,0.018 MODE=2,2,2,1
*THERM
  NPT=5 TI=0.,24000.,57600.,64800.,64908. TEMP=900.,534.583,23.,650.,650.
*SOLVER
  METHOD=1 NPT=5 TI=0.,24000.,57600.,64800.,64908. STP=250.,40.,40.,0.2
*DEBOND
  NII=1
#  DBCH=1 NBI=1 NGI=1 FACE=2 BDN=7. LN=0.0001 BN=60. TOLN=0. &
#  BDS=40 LS=0.1 BS=100. DELAY=64800.
  DBCH=2 NBI=1 NGI=1 FACE=2 BDN=7. LN=0.0001 BN=8. TOLN=0. &
  BDS=40 LS=0.1 BS=100 DELAY=64800.
*PRINT
  NPL=6
*XYPLOT
  FREQ=1
  MACRO=1
   NAME=example_5e X=3 Y=9
  MICRO=1
   NAME=example_5e IB=1 IG=2 X=3 Y=9
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (***CONSTITUENTS**) [KM_2]:

Number of materials:	2	(NMATS=2)
Materials:	SiC fiber	(MATID=E)
	Ti-21S	(MATID=A)
Constitutive models:	SiC fiber: linearly elastic	(CMOD=6)
	Ti-21S matrix: Isotropic GVIPS	(CMOD=4)

3) Analysis type (***RUC**) → Repeating Unit Cell Analysis [KM_3]:

Analysis model:	Doubly periodic GMC	(MOD=2)
RUC architecture:	Square fiber, rectangular pack	(ARCHID=11)
Unit cell aspect ratio:	0.9	(R=0.9)
Fiber volume fraction:	0.35	(VF=0.35)
Material assignment:	SiC fiber	(F=1)
	Ti-21S matrix	(M=2)

4) Loading:

a) Mechanical (***MECH**) [KM_4]:

Loading option:	3	(LOP=3)
Strain reference time:	57600. sec.	(REFTIME=57600.)

Number of points:	5	(NPT=5)
Time points:	0., 24000., 57600., 64800., 64908. sec.	(TI=0.,24000.,…)
Load magnitude:	0., 0., 0., 0., 0.018	(MAG=0.,0.,…,0.018)
Loading mode:	stress/strain control	(MODE=2,2,2,1)

b) Thermal (***THERM**) [KM_4]:

Number of points:	5	(NPT=5)
Time points:	0., 24000., 57600., 64800., 64908. sec.	(TI=0.,24000.,…)
Temperature points:	900., 534.583, 23., 650., 650. °C	(TEMP=900.,…,650.)

☞ Note: The second temperature (534.583 °C) is chosen in order to preserve the rate of change of the temperature.

c) Time integration (***SOLVER**) [KM_4]:

Time integration method:	Forward Euler	(METHOD=1)
Number of points:	5	(NPT=5)
Time points:	0., 24000., 57600., 64800., 64908. sec.	(TI=0.,24000.,…)
Time step sizes:	250., 40., 40., 0.2 sec.	(STP=250.,40.,40.,0.2)

5) Damage and Failure:

a) Fiber-matrix debonding (***DEBOND**) [KM_5]:

```
  NII=1
#  DBCH=1 NBI=1 NGI=1 FACE=2 BDN=7. LN=0.0001 BN=60. TOLN=0. &
#  BDS=40 LS=0.1 BS=100. DELAY=64800.
  DBCH=2 NBI=1 NGI=1 FACE=2 BDN=7. LN=0.0001 BN=8. TOLN=0. &
  BDS=40 LS=0.1 BS=100 DELAY=64800.
```

No. debonding interfaces:	1	(NII=1)

CCI Model		(DBCH=1)
Interface subcell indices:	1, 1	(NBI=1 NGI=1)
Interface identifier:	x_3-interface	(FACE=2)
Normal debond stress:	7. ksi	(BDN=7.)
Normal Λ parameter:	0.0001 /ksi	(LN=0.0001)
Normal B parameter:	60. s	(BN=60.)
Load reversal tolerance:	0. ksi	(TOLN=0.)
Shear debond stress:	40. ksi	(BDS=40.)
Shear Λ parameter:	0.1 /ksi	(LS=0.1)
Shear B parameter:	100. s	(BS=100.)
Debond time delay	64800. sec.	(DELAY=64800.)

ECI Model		(DBCH=2)
Interface subcell indices:	1, 1	(NBI=1 NGI=1)
Interface identifier:	x_3-interface	(FACE=2)
Normal debond stress:	7. ksi	(BDN=7.)
Normal Λ parameter:	0.0001 /ksi	(LN=0.0001)
Normal B parameter:	60. s	(BN=60.)

Load reversal tolerance:	0. ksi	(TOLN=0.)
Shear debond stress:	40. ksi	(BDS=40.)
Shear Λ parameter:	0.1 /ksi	(LS=0.1)
Shear B parameter:	100. s	(BS=100.)
Debond time delay	64800. sec.	(DELAY=64800.)

The input format for debonding shown above involves first specifying the number of interfaces that could possibly debond, then specifying the required data for each of these interfaces. MAC/GMC 4.0 treats the normal and shear debonding at a particular interface independently. Thus, independent normal and shear values for the debond stress (σ_{DB}), Λ parameter, and B parameter are required for each interface that is permitted to debond. In addition, a normal load reversal tolerance (TOLN) and a debond time delay (DELAY) must be specified for each interface. The normal load reversal tolerance is the stress below which the model treats the normal interfacial stress as zero, thus allowing the interface to close and support compressive stress. This can become important in cyclic load cases. The debond time delay is the time at which the code begins to consider the possibility of debonding. Before this time, the interface is treated as perfectly bonded independently of the other specified parameters. For more information on the debonding models and the associated input requirements, see the MAC/GMC 4.0 Theory Manual Section 5.4 and the MAC/GMC 4.0 Keywords Manual Section 5.

☞ Note: In order to execute the three cases presented in the results for this example, the appropriate lines under ***DEBOND** must be commented and uncommented.

6) Output:

a) Output file print level (***PRINT**) [KM_6]:

Print level:	6	(NPL=6)

b) x-y plots (***XYPLOT**) [KM_6]:

Frequency:	1	(FREQ=1)
Number of macro plots:	1	(MACRO=1)
Macro plot names:	example_5e	(NAME=example_5e)
Macro plot x-y quantities:	ε_{33}, σ_{33}	(X=3 Y=9)
Number of micro plots:	1	(MICRO=1)
Micro plot names:	example_5e	(NAME=example_5e)
Micro plot subcell indices:	1, 2	(IB=1 IG=2)
Micro plot x-y quantities:	ε_{33}, σ_{33}	(X=3 Y=9)

7) End of file keyword: (***END**)

Results

Figure 5.12 shows the predicted transverse tensile response of the composite at 650 °C for the three different cases (perfect bonding, debonding represented by the CCI model, and debonding represented by the ECI model). Both the global (composite) stress vs. strain response and the local interface stress vs. global strain response are plotted for each case. In the case of perfect bonding, the interfacial stress is higher than the composite stress at a given global strain level. Including fiber-matrix debonding in the simulation via the CCI model has a major effect on the transverse response. The obvious "knee" in the composite curve corresponds to the onset of fiber-matrix debonding. The interface response predicted by the CCI model is identical to the perfectly bonded interface behavior until debonding occurs. Then the interfacial stress quickly saturates to a nearly constant value. Since the interface can support no additional stress, the intact region of the composite is placed under greater stress and flows to a greater extent. Finally, in the case of the ECI model, after the interface debonds, the interfacial stress unloads. This is thought to be the more accurate mechanism as a debonded interface cannot support stress. Now the intact region of the composite must not only support the additional applied load, but also the stress that is unloaded from the interface. This causes even more flow in the intact region, and a composite stress strain curve that is considerably more compliant than that predicted using the CCI model. Note that residual stresses were incorporated in the present example, which is why the interfacial stresses plotted in Figure 5.12 are compressive at zero applied global strain.

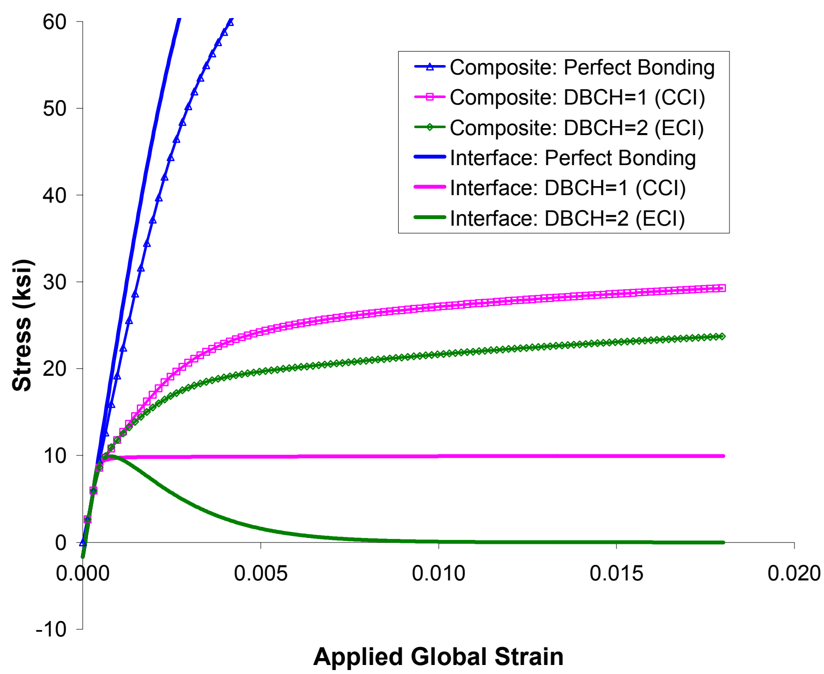

Figure 5.12 Example 5e: Predicted local and global transverse stress-strain response of 35% SiC/Ti-21S at 650 °C with fiber-matrix debonding.